7th European Conference on Industrial Engineering and Operations Management
Augsburg, Germany, July 16-18, 2024
Publisher: IEOM Society International, USA DOI: 10.46254/EU07.20240102
Published: July 16, 2024

Reviewing Potential of Digital Twin Technology to Facilitate Sustainability in Manufacturing

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Abstract

The fourth industrial revolution is urging the traditional manufacturing sector to explore the potential of digital twin (DT) technology for digitalization, optimized production, and sustainable manufacturing practices. Digital twins provide a way to support decision-making towards efficient production and cost saving using the digital version of a physical asset. In the literature, several studies are available focusing on the connection between digital twin technology and intelligent manufacturing. However, the literature lacks information about how digital twin technology complements sustainability in manufacturing. There is unexplored potential in how digital twin technology can contribute to advancing sustainable manufacturing practices by providing real-time monitoring and process optimization, resulting in lower environmental impacts. The presented study explores digital twin technology concerning the sustainability aspects of the manufacturing sector. Real-time monitoring and analysis of a digital manufacturing system provide an opportunity to optimize energy, reduce waste, minimize failures and maintenance needs, and enhance supply chain efficiency. The current study reviews DT technology with respect to various aspects of sustainable manufacturing, such as reduction in energy consumption, reduction in waste streams, maintenance and failure prediction, supply chain aspects, and design for sustainability (DFS). The study will provide futuristic recommendations to help manufacturers meet their sustainability goals.

Keywords
Digital Twin; Sustainable Manufacturing; Cost Saving; Optimized production; Waste Reduction

1. Introduction
Digital technologies are gaining popularity in different industrial sectors such as energy, automotive, manufacturing, waste management, and aerospace etc. to address the challenges associated with real-time monitoring, data governance, decision making, and complex data integration etc. Among other digital technologies, digital twin has shown immense potential to solve these said challenges (Ali et al. 2022). Digitalization has been realized as a strong enabler for the industry 4.0. Digital Twin is an exact digital version or data-driven virtual replica of a physical system. This digital copy is linked with the physical system using real-time data monitoring, and has ability to simulate the behavior and its performance. With the advent of Industrial internet of things (IIoT), digital twin has emerged as potential transformative force to address the linkage between virtual and physical spaces. Digital twin can also predict

about the health of a physical system, identify potential problems and recommend optimization of the system (Hartmann and Van 2021).

Currently all mentioned sectors and related businesses exploring the potential of digital twins, and it is worthy to mention that digital twin technology has been picked by Gartner's Top 10 Strategic Technology Trends consecutively three years in a row (Panetta 2017). As shown in the Figure 1, it can be seen that the concept of digital twin technology was originated in 1960s when mathematical tools were used to simulate the physical phenomenon by scientific and engineering communities. In the next era, different computer aided design, manufacturing and engineering-based software tools were introduced to handle complex geometries and facilitate engineering computations.

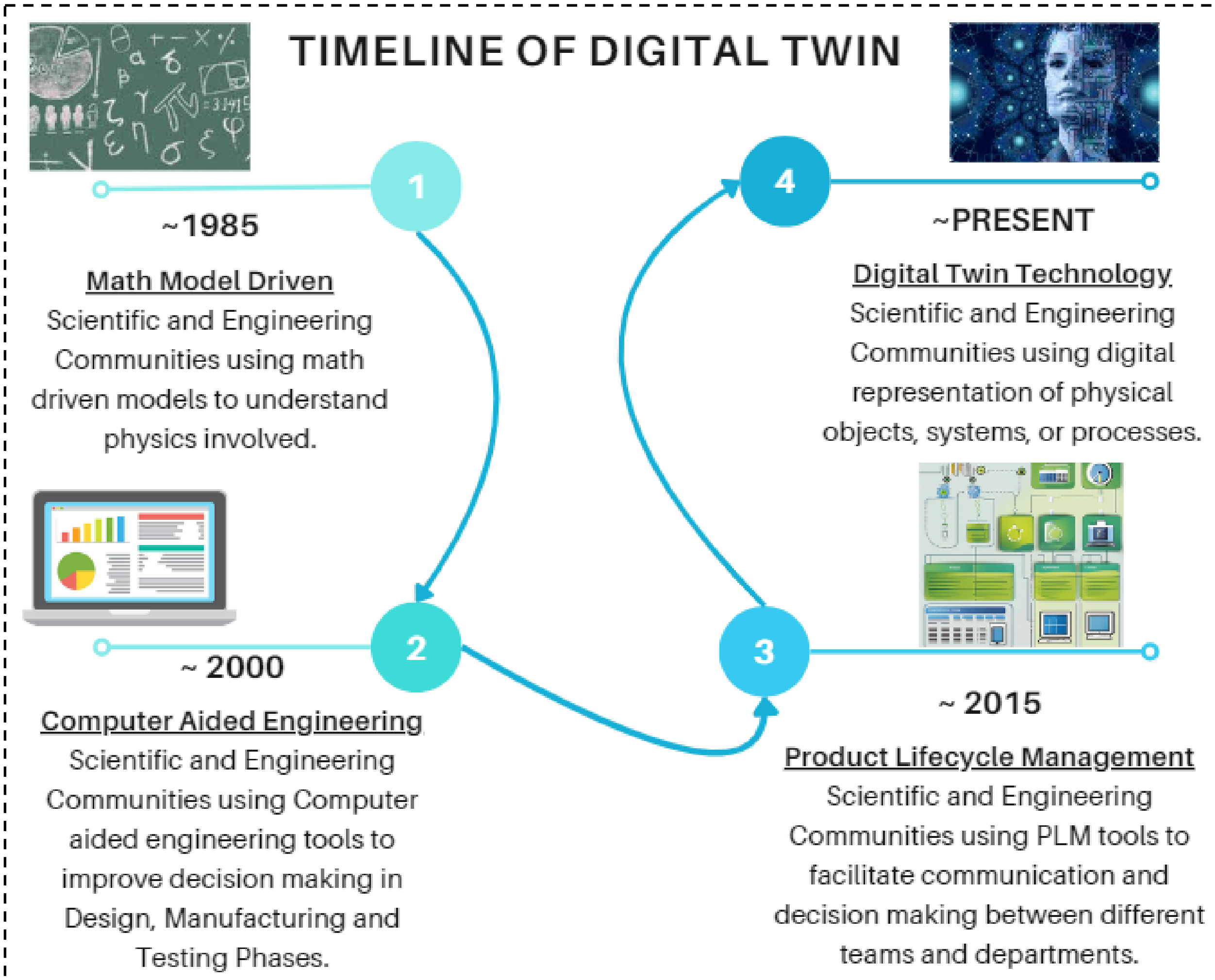

Figure 1. Evolution of Digital twin technology (timeline)

The next phase demonstrates the natural progression of computer-aided technologies towards the formation of a more integrated information management solution for the entire life cycle of a product, referred to as Product Lifecycle Management (PLM). The PLM tools were focused on integrating the data through various phases of the life cycle of a product starting from design, manufacturing and end-of-life phases. Natural extension of this concept transformed into the digital twin technology, where the static nature of data integration was replaced with the real-time data availability and resulting in dynamic monitoring and analysis. The notion of digital twin technology is considered as a possible solution for the manufacturing sector, as it deals extensively with physicals objects, related processes and input-output behaviors (Kholopov et al. 2019). In case of manufacturing sector there are several studies where concept of digital twin has also been practiced on the processes as well (Shao 2023).

Literature also mentions reference framework to implement the digital twin technology in the manufacturing sector under the guidance of ISO -23247 standard (ISO 2021. ISO 23247-1 2021). The standard provides opportunity to manufacturers by selecting the relevant subsystems and components to build and implement a case-specific digital twin. The ISO-23247 standard consists of four layers as shown in Figure 2. The first layer is comprised on the noticeable manufacturing elements. The second layer is composed of the communication entities. This layer monitors changes in the state of manufacturing elements and triggers the signal to control program to take any necessary adjustments. The digital twin entity represents the third layer. It retrieves and processes data from the previous communication layer to update the existing models. The fourth layer hosts user entities, where applications are present to enhance manufacturing efficiency (Guodong et al. 2023)(ISO TC184 SC4 WG15 2020).

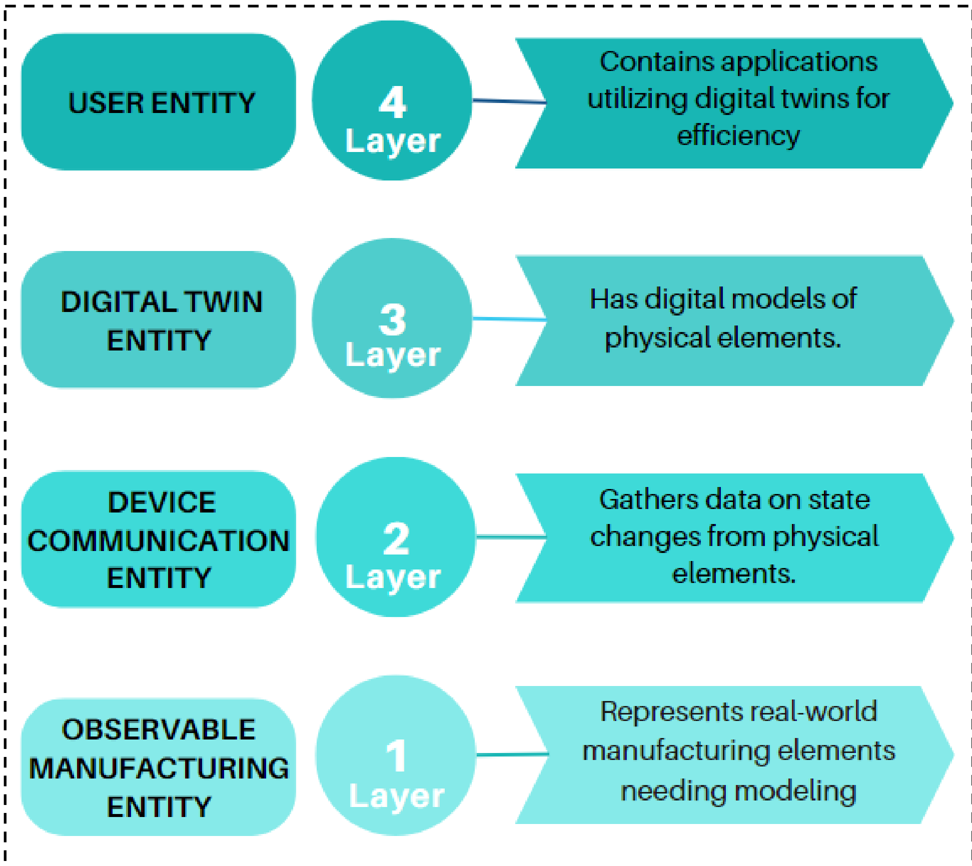

Figure 2. Framework proposed by ISO – 23247

Literature points out at the following disciplines of the manufacturing sector where it has provided improvement towards the productivity and efficiency.

2. Digital Twin Technology in Energy Management

Manufacturing sector has several case studies and published literature where digital twin technology was successfully implemented to optimize the energy consumption of system. It is believed that for manufacturing sector, digital twin can enable different themes in the manufacturing domain such as industry 4.0, smart manufacturing and industrial internet of things. Mohammed et al. (2023) investigated the energy consumption optimization using digital twin technology. The cost related to any product can be significantly high due to high cost involved in the manufacturing phase especially when dealing with chemicals, iron and steel manufacturing. In manufacturing phase major component of cost comes from the energy cost. Figure 3 shows the input and output inventory for a manufacturing process. The role of energy can be seen for both input and output streams (Mohammed et al. 2023). The study revealed the potential application of digital twin towards production supervision, fault detection, logistic flow, and building management.

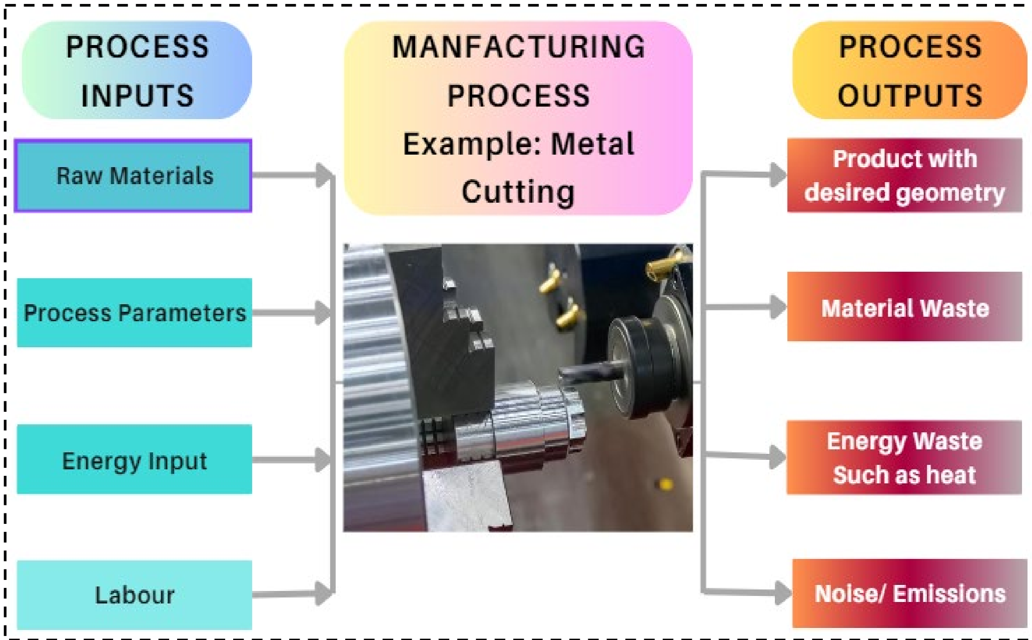

Figure 3. Manufacturing process input and output inventory

Perossa et al. (2022) explored the potential of digital twin technology towards the energy consumption management (ECM) during the production phase. The study pointed out at the various areas of energy application using digital twin technology. It has been revealed that digital twin can be used to monitor energy, predict energy consumption, reduce energy wastage, optimization of process and related maintenance, and optimization of energy-based parameters. Keeping in view the nature of processes and applications involved, more work is needed to analyse correlation between the digital twin features and energy consumption management.

Santos et al. (2022) investigated the energy consumption during the robotic drilling process by utilizing the concept of digital twin. The study was conducted by using simulation using Siemens Tecnomatix software. The study utilized design of experiments (DOE) to study the energy consumption. The virtual readings were verified using the experimental work as well using a robotic drilling cell. The study provided encouraging insights about creating a virtual replica of actual robotic drilling process. In another study, Stan et al. (2023) has conducted an investigation where digital twin application was explored towards the process planning and robotic programming of robotic deburring process. The study also incorporated the image processing technique to wisely re-machine the regions where burr was not removed. The study incorporated a web-based platform to monitor the operation, trigger alarms if needed and allow permission to control by an authorized person. Wu et al. (2021) in another study, investigated the implementation of digital twin towards the intelligent factory using artificial intelligence technology. The study was focused on the energy consumption of the intelligent factory. The study revealed that feature recognition accuracy was as high as 89.23% that was found better than the existing models available in literature. The study provided a futuristic direction that the concept is also helpful for the smart cities.

Lima et al (2022) focused on lowering the energy consumption of production lines by simulating the scenario. The study was dedicated to the theme of industry 4.0. To facilitate the decision making, once the model was prepared a machine learning algorithm was also implemented. Davila R et al. (2023) revealed another aspect of digital twin technology where it was proposed as a tool to facilitate sustainability in the manufacturing sector. The proposed architecture was shown in Figure 4. It has four levels. Level 1 shows the modeling of manufacturing processes. Level 2 shows pre-processing stage, where gathering of data is performed. Level 3 is based on analytics, where assessment of sustainability is performed using the relevant information. Level 4 shows the virtual representation of data to support decision making. The digital twin model was composed on the two segments namely the energy efficiency of production and privacy preserving in supply chain.

Zhang et al. (2018) explored the implementation of equipment energy consumption management (EECM) within the context of a digital twin shop-floor (DTS). It presents a novel framework for achieving effective EECM and investigates its potential applications in areas such as real-time energy consumption monitoring, in-depth data analysis, and optimization strategies.

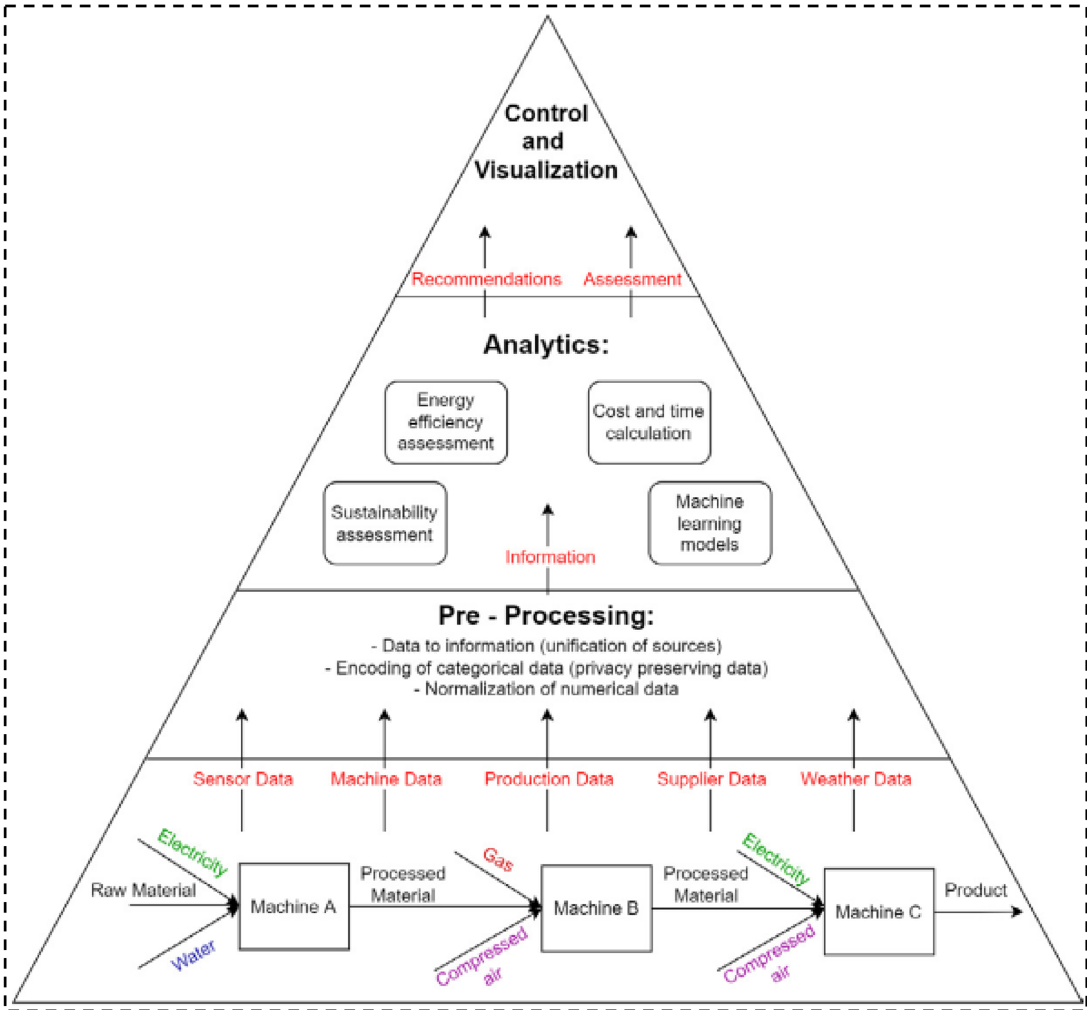

Figure 4. Architecture of sustainability digital twin (Davila et al. 2023)

3. Digital Twin Technology in Waste Management

Another important outcome in the manufacturing sector is linked with the reduction of waste produced. Several researchers have focused their work to reveal the potential of digital twin towards waste management. Soleymanizadeh et al. (2023) conducted a study and provided insights to readers that digital twin can act as an enabler for several manufacturing concepts just as lean, just-in-time, agile, flexible and green. The study revealed the potential that digital twin can identify bottlenecks in production and also reduce waste. Digital twin technology can also be used by manufacturers to anticipate better towards changing customer needs. Zhang et al. (2023) developed intelligent digital twin to support paper making industry. The model successfully monitored critical parameters, and intelligent control improved the decision making that resulted in higher operational efficiency by reducing waste, labor and maintenance.

In order to have efficient recycling in waste plant, sorting is very demanding task due to its heterogeneous nature. Kroell et al. (2024) developed a digital twin of waste sorting plant. It is worth mentioning that sensor-based process monitoring was combined with the machine learning technique. Figure 5 shows the virtual model of a sorting plant that can be simulated to control and optimize process in real-time manner.

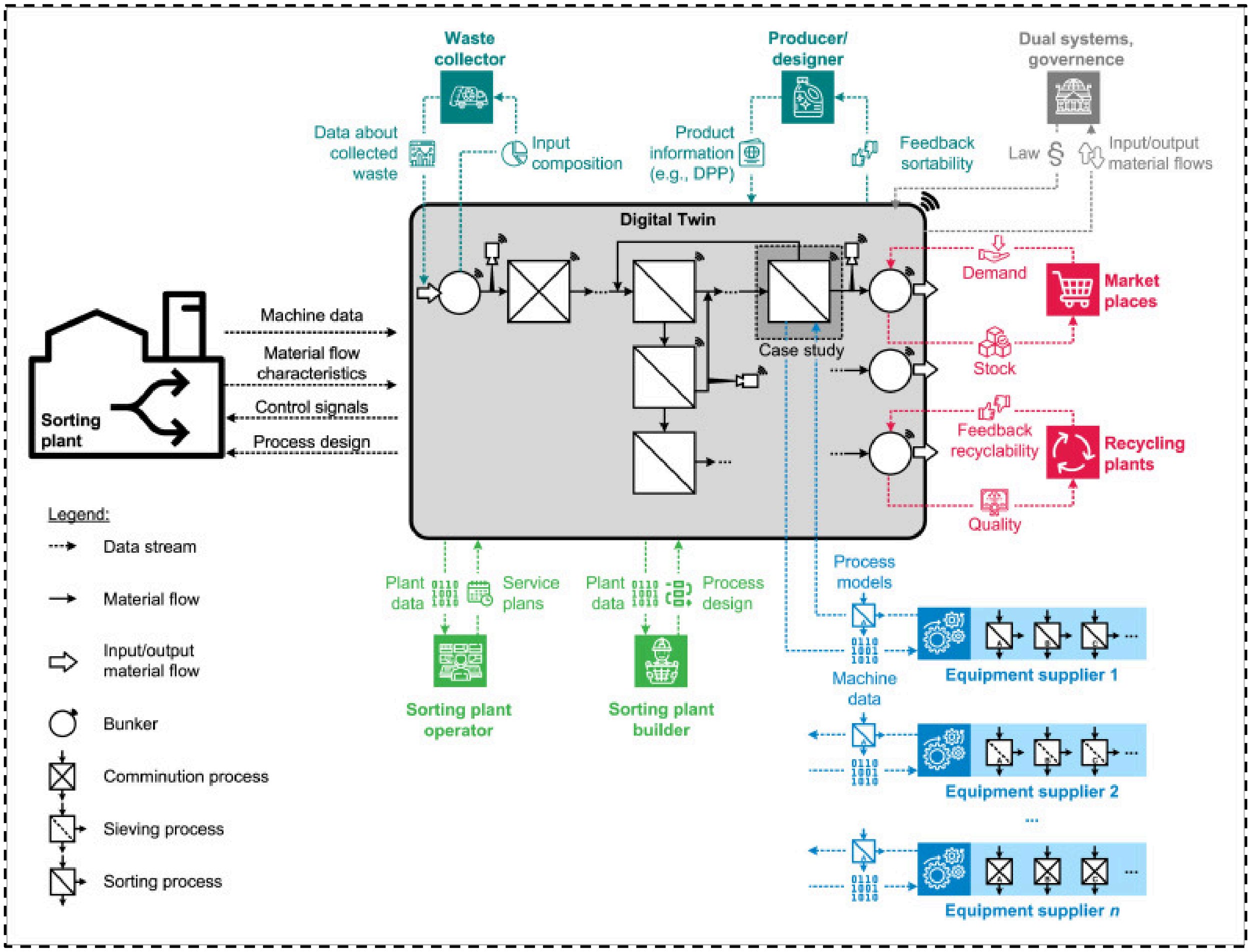

Figure 5. Digital twin concept of waste sorting plant (Kroell et al. 2024)

4. Digital Twins in Supply Chain Management

The supply chain is a broader context that comprises not only manufacturing aspects but also includes all functions involved in receiving and delivering customer orders (Chopra and P. Meindl 2016). Some of these functions are procurement, manufacturing, warehousing and distribution, transportation, order processing and aftersales services. Overall, the objective of the supply chain is to increase supply chain surplus; hence, the complexity of supply chain is much higher than individual functions such as manufacturing. Moreover, information requirements across supply chain are higher than individual functions. There have been a few studies found in the literature which probe the role of digital twins for supply chains. Some of the studies have been discussed below. Barykin et al. (2020) reported that the scientific research community is contemplating on the need to use DTs for managing supply chain risks. They discussed the supply chain risks in two contexts: the first caused by supply chain disruptions because of operational uncertainties such as uncertainty in demand and supply. The second type is because of risks associated with natural disasters and man-made affects such as disruptions caused by floods and fires, wars and legal di-sputes etc. They reported dynamic simulation and analytical optimization as the key approaches for mitigating the supply chain risks.
Mosheed et al. (2021) explored the role of Digital Twins to improve Supply Chain visibility within the logistics domain. The study reviewed over hundred research articles from 2002 to 2021 for their investigation and found that digital twin technology has a positive correlation with supply chain visibility. The study further suggested that the technology should be implemented on a small scale in the beginning and then its scope could be enhanced gradually.

They concluded that the application of digital twin technology in the logistic domain is a very novel research area and for many companies its implementation will serve as a strategic goal. Valk et al. (2022) reviewed existing literature on the topic of Digital twin in Supply Chain Management. Particularly, they explored the extent to which DTs have been used in the Supply Chains. The researchers identified four hundred ninety-seven related publications and used seventy-five relevant publications to analyse their findings. They found the most prominent area using the DT technology was manufacturing. The researcher identified key research gaps including the Supply Chain Control through DT, and a focus on domains other than production.

Barykin et al. (2021) identified a gap in understanding terminologies such as digital twin and digital economy in context of industry 4.0 and explored how they can be implemented in the supply chain context. They highlighted the urgent need to convert supply chain models into digital models. Badakhshan and Ball (2022) investigated how digital twins can be used to improve inventory management and cash conversion cycle in the supply chains. They further argued that the literature on supply chain digital twins is in the very early stages and requires further research on the deployment of digital twins. Srai et al. (2019) reported that although the concept of digital twin is very new, however, its application has emerged across supply chains context. They discussed how variability in the demand can be predicted using digital twins. Le and Fan (2023) emphasized the need to develop a digital twin conceptual framework for supply chains to enable efficient and transparent decision making.

In the sustainability context, very few studies have been found in the literature. Furthermore, in the context of closed loop supply chains, Preut et al. (2021) stated that the information requirements for closed loop supply chain are higher than those for the open loop supply chains. They further reported that the application of digital twins in the closed loop supply chains is in its infancy. Singh et al. (2023) pointed out that it is hard to find research literature on the role of digital twins in supply chains. The researcher's focus was from a sustainability perspective. They collected data from more than 200 participants in the manufacturing sector to find the impact of digital twins on supply chains. Their findings suggest that digital twins can greatly enhance the operational efficiency of supply chains. Chen and Huang (2021) analyzed two hundred and eighty-eight research articles to explore potential uses, challenges and solutions of digital twins in remanufacturing supply chains. Their findings suggest digital twins have the potential to solve information asymmetries in the remanufacturing supply chains.

All of the above studies indicate that the research in the use of digital twins for supply chain is in very early stages and requires attention of researchers to exploit the potential of DTs to improve overall supply chain efficiency and responsiveness. Several factors may contribute to the limited use of digital twins in the supply chain domain. First, the DT technology is comparatively new and there is a lack of awareness about the technology. As the technology is emerging, not so many people are aware of its potential benefits and how it will change the future landscape of supply chains across the globe. Secondly, companies and organizations lack skilled workforce who can implement the technology. There is a great opportunity for supply chain companies to proactively train their workforce to exploit the benefits of digital twin technology. Finally, the implementation of DT technology requires a significant amount of investment and time, which not many companies are willing to dedicate. In summary, a great potential of the application of DT technology across the supply chain has been observed. Figure 6 shows a conceptual framework of the DT technology can be used across the supply chain for information sharing and decision making.

5. Digital Twins in Design for Sustainability

Design For Sustainability (DFS) as defined by Rocha et al. (2019) is "a holistic design approach that enables the integration and assessment of sustainability dimensions at various stages of the product or product-service development process, facilitating the necessary scale of incremental and/or radical innovations". Mayyas et al. (2012) describe DFS in terms of following DFX objectives: (1) Design for Functionality, (2) Design for Manufacturability, (3) Design for Resource Utilization and Economy, (4) Design for Environmental Impact, (5) Design for Recyclability/Manufacturability, and (6) Design for Social Impact. In summary, DFS is a comprehensive design approach covering various stages and objectives of product or product development process.

To the best of authors' knowledge, no previous research has been found that exclusively cover all DFS aspects in reference to the potential of digital twins. However, researchers have investigated role of DT technology for assessing sustainability in general. For instance, He and Bai (2021) discussed potential of DT technology for sustainable intelligent manufacturing. Li et al. (2020) proposed digital twin driven information architecture for sustainability assessment. Barni et al. (2018) found no existing studies on exploring the role of DT technology for sustainability improvement across the value chain. They proposed a reference architecture to assess sustainability performance of production system.

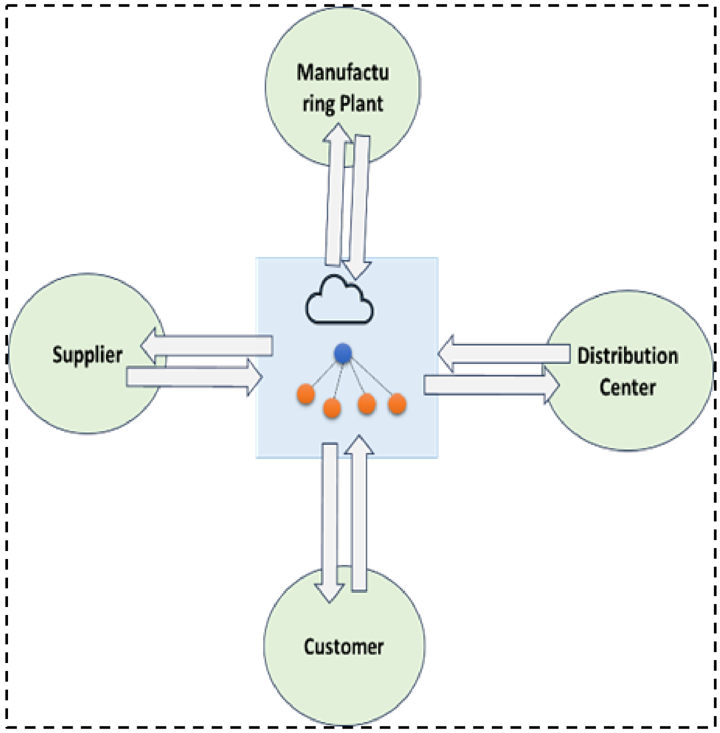

Figure 6. Conceptual framework of Digital Twins for information sharing and decision making across supply chain

Similarly, many other researchers have also reported the potential of the DT technology for assessing and improving sustainability. However, there is a long way to the full exploitation of the DT technology for achieving sustainability across the value chain. Furthermore, most of the studies are of conceptual nature lacking implementation of the DT technology to achieve DFS objectives discussed above. Authors foresee an increasing potential of DT technology to capture data in real time, analyzing it and using it to achieve DFS objectives. So, there is a great opportunity available in this research direction.

6. Digital Twins in Maintenance

In manufacturing industry, repair, maintenance and overhaul is a major function and business unit. Maintenance has various different types (Errandonea et al. 2020) but it can generally be divided into three main categories of corrective maintenance i.e., reactive maintenance, preventive maintenance or scheduled maintenance, predictive maintenance or data-based maintenance (Nakagawa 2005). Since digital twins are basically data models or the real world that are connected to the real-world entities (Nakagawa 2005), they have the potential to improve predictive or condition-based maintenance to optimize the use of equipment and resources (Errandonea et al. 2020). Implementation and application of advanced IT systems and technologies such as digital twins in traditional manufacturing equipment particularly in SMEs and the presents an integration and convergence challenge (García et al. 2024).

Zhong et al. (2023) presented a review of digital twins for predictive maintenance. This was a relatively high-level review which can perhaps be extended. Dinter et al. (2022) presented a comprehensive review of the digital twins. This review paper should be used by researchers within the field to build a basis of further research. However, this review was conducted more from a statistical point of view using the Systematic Literature Review (SLR) methodology. A detailed technical review of key papers will be required when focusing on a narrowed down area of research within the broader field of maintenance and digital twins.

Most researchers pointed to the lack of unified and standardized framework for Digital twins for maintenance. Gacia et al. (2024) highlighted the need for standardized models for digital twins. In this regard, You et al. (2022) attempted to cypher a generic model for digital twins for predictive maintenance as shown in Figure 7. Whereas this model provides an understanding of high-level architecture and basic system components, significant work will be required to make use of such model for developing any digital twin for predictive maintenance. Moreover, integration and working of the model need to be ensured with the whole system.

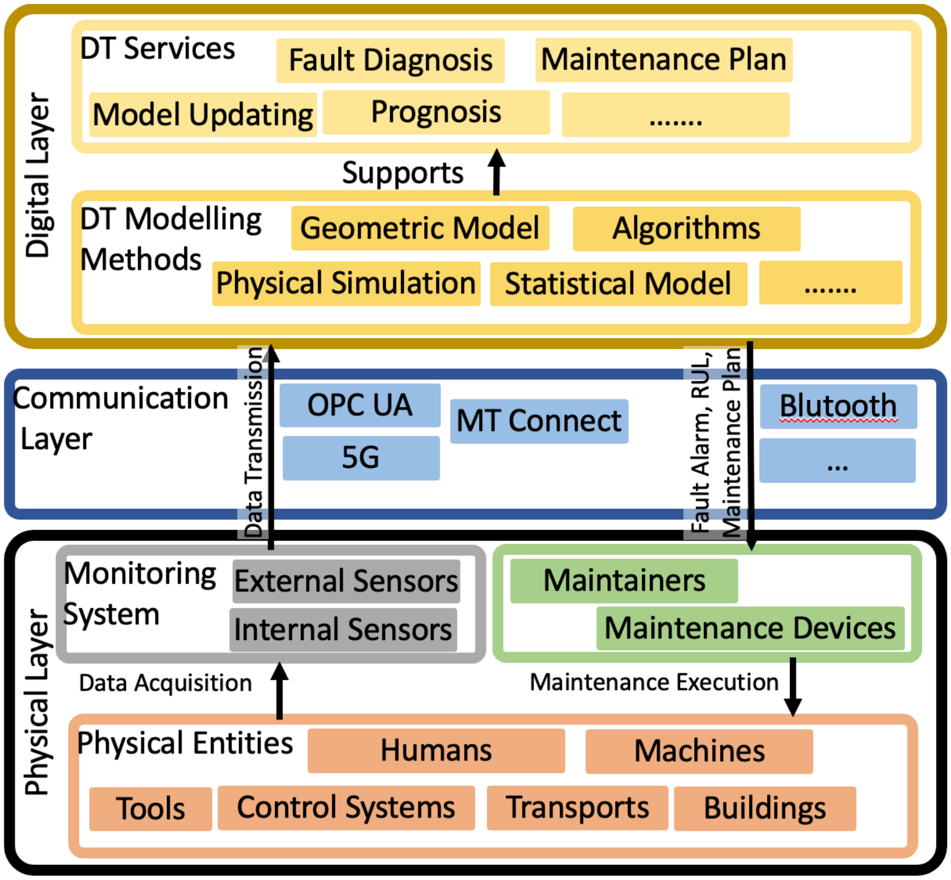

Figure 7. A generic model for digital twins for predictive maintenance adapted from (You et al. 2022)

Some researchers have highlighted for reference model rather than a standardized model for DT for maintenance (Josifovska et al. 2019, Lu et al. 2020, Schleich et al. 2017). Others have highlighted the limitations of reference and standard models and have argued for ontological models as they not only provide a reference but also the important constraints and axioms for building a digital twin for maintenance (Schleich et al. 2017).

7. Conclusions

The following conclusions can be drawn from the review of existing literature on DT technology in energy management, waste management, supply chain management, design for sustainability and maintenance:

- There is need to have more focused research related to the digital twin shop-floor modeling to reduce and optimize the energy consumption involved. Also, the data management and fusion from multiple sources require more dedicated research efforts.
- The digital twin framework can significantly support the management capability of waste streams. It can reduce operating costs, improve safety levels, and handle accidents more efficiently. The framework can also help in achieving lean practices.
- Only a handful of studies have been conducted on the potential of Digital Twin technology for supply chain management (SCM) and design for sustainability (DFS). This suggests that research in this direction is still in a very preliminary stage.
- Most of the available literature focused on the review of digital twins for SCM and DFS. The findings of these studies strongly suggest that Digital Twin technology has great potential to improve sustainability and efficiency across supply chain. However, the literature lacks implementation of Digital Twin technology in these domains.

- Digital twin and maintenance appear to be reducing machine or equipment downtimes and increase Remaining Useful Life (RUL) which is very promising. Small and Medium Enterprises (SMEs) appear to be missing out on benefits of Digital Twin for maintenance. Researchers need to divert attention towards SMEs in this regard.
- There is a clear need for high level reference ontological model for maintenance for and Digital Twins. This is because a standard model or detailed reference model may not fit for all. An ontological approach on this regard should be explored. Researchers within the field of Digital Twins for maintenance need to broadly focus on predicative maintenance and digital twins.
- Narrowed down area of research within predictive maintenance will require extensive review with focus on technical detailed rather than statistical focus as found in most reviews. A reference framework or model for maintenance and digital twins is largely missing and should be focused on to avoid dispersed research efforts.
- Future research can focus on implementing Digital Twin technology in real-life use case scenarios. The identification and use of appropriate Digital Twin tools are key to the success of implementation.

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Biographies

Dr. Usman is a Chartered Engineer (CEng MIMechE) with experience in manufacturing engineering in both industrial and academic environments. He has a PhD in Manufacturing Informatics. He is working as a Principal Digital Manufacturing Engineer at ITP Aero UK. Dr. Usman worked in Rolls Royce as Lead Digital Manufacturing Engineer where he lead the biggest ever deployment of Manufacturing Execution Systems in RR history at that time. He continues to work toward digitizing various business functions to improve efficiency. He has worked as a Lecturer at Coventry University and as Researcher at Loughborough University within the areas of Robotics, Digital Manufacturing, Automation and Manufacturing Interoperability. He has extensive experience of project management, team leadership, production planning, scheduling and a track record of successful delivery.

Dr. Imran is currently serving as an Assistant Professor of Industrial Engineering in the Mechanical and Industrial Engineering department at RIT Dubai. He earned his PhD in manufacturing engineering from Loughborough University in the UK. Dr. Imran's doctoral research focused mainly on semantic data modeling and interoperability in manufacturing systems. Dr. Imran also completed his master's degree in advanced manufacturing engineering and management from the same university, with his major project focusing on knowledge-based tools. Before joining RIT Dubai, he had more than 10 years of experience working in the higher education sector. Dr. Imran has experience working on various committees in different roles and has taught a range of courses at both the undergraduate and graduate levels. He has also been involved in curriculum development and program evaluation to meet the requirements of various accreditation bodies. Currently, Dr. Imran is engaged in teaching undergraduate and graduate courses at RIT Dubai.

Dr. Pervaiz received his PhD in Production Engineering from KTH Royal Institute of Technology, Sweden in 2015. While pursuing his PhD, Dr. Pervaiz has worked on a Swedish Industry (Accu-Svenska AB) supported project for the development of an advanced minimum quantity cooling lubrication (MQCL) system to facilitate the sustainable environment friendly machining of aeronautic titanium alloy (Ti6Al4V). Dr. Pervaiz’s research is mainly focused on the advanced topics of sustainable manufacturing. The research has made significant contributions in the field of environment friendly machining and associated numerical simulations. The research also incorporated novel computational fluid dynamic model to study the influence of cooling media and temperature distribution in the metal cutting process. The research outcomes have advanced the state of the art in the metal cutting to make machining more environment friendly in nature. Dr. Pervaiz has taught several undergraduate and graduate level courses in the broader area of design and manufacturing. His teaching methodology incorporates the element of experiential learning by providing students the opportunities to gain ideas of multidisciplinary team work and hand on experience..